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Statistical modelling of turbidity removal applied to non-toxic natural coagulants in water treatment: a case study

Statistical modelling of turbidity removal applied to non-toxic natural coagulants in water treatment: a case study

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Abstract

An investigation into two non-toxic natural coagulants abundantly growing in different countries, cactus (*Opuntia spp*.) and okra was performed on monthly river water samples (one-year period). The studied case was the Euphrates river/Al-Mashroo canal/Iraq. Six statistical models were interpreted and tested describing the residual turbidity after Coagulation-Flocculation for the three studied cases (Optimum-Coagulant-Dose, Optimum-Flocculator-Velocity-Gradient and Optimum-Flocculation-Time). According to the environmental parameters recorded during the study and the statistical analyses, two facts were concluded. The first fact was that controlling the Optimum-Flocculator-Velocity-Gradient of the Coagulation-Flocculation process gave the highest contribution ratio of the models. The second fact was that the most significant environmental parameter (statistically) in the Coagulation-Flocculation process was the initial turbidity. This was proved for the two natural coagulants under study. Also, from the results of the study, it was concluded that the two natural coagulants were of similar coagulation-flocculation properties, and they were competent for turbidity removal.

Key words: Natural coagulants; Coagulation-Flocculation; Turbidity removal; Statistical Modelling.

1. Introduction

The coagulation process, which is a process of destabilising colloids by reducing the zeta potential to agglomerate the colloids together forming small flocs, is a central part of chemical treatment of water and wastewater [1-5]. The addition of chemical coagulants into the aqueous media could be done either chemically (directly addition of solid chemicals) or electrically (electrochemical methods) [6, 7]. The direct addition method requires larger amount, of coagulants, than the electrochemical methods [6]. In addition, the direct addition method produces large volumes of sludge [5, 6]. Then, the generated flocs will be removed from the solution using one of a number of different methods [8-10]. Although a large number of chemicals have been used as coagulants, aluminium sulphate (alum) is the commonly used coagulant in many countries [6, 11, 12]. Recently there have been many rumours about a possible link between high levels of residual aluminium and several health issues, such as the development of Alzheimer's disease [13]. In addition, the traditional chemical coagulants generate a huge amount of sludge, which in turn increases the operating cost of treatment plants, because the solid wastes require expensive and complex handling and management systems [5, 14, 15]. Therefore, these negative effects of synthetic chemical coagulants have initiated global interest in the search for safe and economic natural coagulants [16, 17]. For instance, Torres and Carpinteyro-Urban [16] applied *Opuntia mucilage* and *Prosopis galactomannan* to treat the elevated chemical oxygen demand (COD) of municipal wastewaters. The *Opuntia dillenii* solution shows very good performance in terms of clarification of very turbid water (186-418 NTU) [18]. Additionally, the cactus leaf extracts showed a good flocculating activity [19]. Taa, Benyahya and Chaouch [20] successfully extracted and applied a bio-flocculent, from the racket of *Opuntia ficus indica*, in the treatment of synthetic industrial wastewater. Vishali and Karthikeyan [21] utilised cactus *Opuntia ficus-indica* as a coagulant for the treatment of a paint effluent wastewater. Furthermore, a number of researchers have investigated the ability of the natural coagulants to remove dangerous pollutants from water. For example, Young [22] successfully applied cactus *Opuntia ficus-indica* for the removal of arsenic from a synthetic water sample. The literature shows that, besides the cactus, okra powder is an effective natural coagulant, where it shows very good efficiency in terms of turbidity and removal of heavy metals [23-25]. For example, Al-Samawi and Hama [23] used okra to remove turbidity from municipal wastewater and leachate of a solid waste sanitary landfill. The outcomes of this study proved the efficiency of okra as a natural coagulant. It is noteworthy to highlight that the literature shows that okra could achieve the maximum turbidity removal at a pH of 8 for medium turbidity level (≤ 150 NTU), and at a pH of 7 for higher levels of turbidity [23, 26, 27].

The current work therefore has been mainly devoted to model the performance of both cactus and okra in terms of turbidity removal from river water taking into consideration the influence of key operating parameters. The specific objectives of the current project are:

1- To prove the competence of cactus and okra for turbidity removal.

2- To study the coagulation-flocculation properties for the two coagulants through a jar tester.

3- To model the residual turbidity at the optimum coagulant dose, optimum velocity gradient and optimum flocculation time, using multiple regression analysis.

It is noteworthy to highlight that the studied water samples were collected from the Euphrates River, at Al-Musayab city, Iraq (this part of the river is known as the Al-Mashroo Canal). The sampling station was located in front of the Al-Musayab water treatment plant, Figure 1. The samples were collected during the period 29/8/2014 until 23/7/2015.

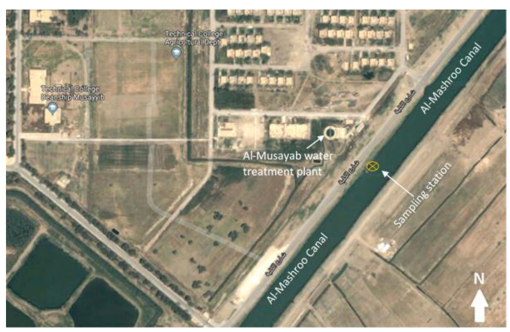

Figure 1: Sampling station

2. Materials and methods

2.1. Standard Solutions

Cactus and okra solutions were prepared according to the standard methods recommended by; Shokralla [28]; [29] and [30]. Standard (0.1%) solutions were prepared for both coagulants daily. The dose was calculated as 1 ml of solution to be equivalent to 1 mg of cactus or okra solution.

2.2. Coagulation-Flocculation in Water Treatment

Coagulation-flocculation properties studied here in this investigation consist of:

1- Optimum-Coagulant-Dose (DO).

2- Optimum-Flocculator-Velocity-Gradient (GO).

3- Optimum-Flocculation-Period (TO).

Here, DO refers to the Coagulant Dose which produces maximum turbidity removal for a constant Velocity Gradient (G1 = 25 1/s) and constant Flocculation Period (T1 = 20 min.). GO refers to the Flocculator Velocity Gradient which produces maximum turbidity removal for a coagulant dose = DO, G1 = 25 1/s and variable T1. TO refers to the Flocculation Period which produces maximum turbidity removal for a coagulant dose = DO, T1 = 20 min and variable G1. Coagulation and flocculation in water treatment have been well defined in the literature; the following references may be consulted for further knowledge about elementary principles: [31-33].

2.3. Optimum dose

For both alum and cactus solutions, the optimum dosage for the studied coagulants has been calculated according to the following procedures [28, 30]:

1. Preparing six beakers (1000 ml each) with raw water from the inlet chamber of the sedimentation tank that delivers raw water from Al-Mashroo Canal.
2. Measuring the initial turbidity, pH level, and temperature.
3. Adding six different doses of the coagulant.
4. Placing the six beakers in the floc-tester ET-750 (jar tester) and rapid mixing for G = 250 (1/s), T = 120 s, and according to Table 1, decide the speed of the mixers (n) according to the raw water temperature.
5. Slow mixing for G = 25 (1/s), T = 20 min, and according to Table 1, decide the speed of mixers (n) according to the raw water temperature.
6. Stopping the mixing and setting the beakers aside for settling for 15 min.
7. Taking samples from the top 30 ml of the beakers and measuring the residual turbidity. This is the clear water turbidity.
8. Drawing the curve between the coagulant dose and residual turbidity to decide the optimum dose that gives the minimum residual turbidity.

For a detailed explanation of the experimental procedure and how to decide the DO, GO and TO, it is recommended to refer to [28, 30].

Table 1: Mixer Speed (n) in terms of Velocity Gradient (G) for different Raw Water Temperatures for LOVIBOND FLOC TESTER ET-750.

G (1/S)	n (rpm)*					
	Raw Water Temperature (°C)					
	10	15	20	25	30	40
25	60	57	55	53	51	47
35	75	71	68	66	63	59
45	88	84	81	78	75	70
55	101	96	92	89	86	80
65	113	108	103	99	96	90
250	277	265	254	244	235	220

*rpm= revolution per minute

2.4. Experimental Work

The appropriate device required for jar testing during the study was the LOVIBOND FLOC TESTER ET-750. Laboratory analysis was performed during the period 29/8/2014 until 23/7/2015. Every point represents results for pH, temperature (TMP), initial turbidity (N_1), residual turbidity (N_2) , DO, GO and TO during a month.

Turbidity Removal Efficiency R (%) was calculated according to the following equation:

$$R(\%) = \left(\frac{N_1 - N_2}{N_1}\right) * 100 \quad (4)$$

Where, N_1 and N_2 represent the initial river water turbidity (NTU) and residual turbidity after coagulation-flocculation (NTU), respectively.

2.5. Statistical Modelling

To manipulate the results, statistical models were built using multiple regression analysis. All theoretical aspects of the above analysis may be found in different statistical textbooks, such as [34] . Within this article, SPSS 20 package was used to perform the stepwise multiple regression analysis. The general multiple regression equation adapted was:

$$Y = a_0 + b_1 X_1 + b_2 X_2 + b_3 X_3 + b_4 X_4 + e \quad (5)$$

Where Y = Dependent variable, a_0 = Intercept, b_1, b_2, b_3, b_4 = Partial regression coefficients, $X_1 X_2, X_3, X_4$ = Independent variables, and e = Error term (residuals). It is noteworthy to mention that e must be normally and independently distributed (NID) with mean μ = 0 and standard deviation σ = 1, (it is written as NID (0, 1)).

In this study, the dependent variable is the residual turbidity (N_2) which will be predicted for three cases:

1- Optimum-Coagulant-Dose (DO).

2- Optimum-Flocculator-Velocity-Gradient (GO).

3- Optimum-Flocculation-Period (TO).

As two coagulants will be investigated, then six models will be explored (3 models for cactus + 3 models for okra) concerning the above cases. For all the models, the dependent variable will be Y = N_2, so that the analysis will be performed for the following cases:

1- Modelling N_2 for the DO

Here the independent variables for both coagulants will be:

X_1 = pH, X_2 =N_1 , X_3 = TMP and X_4 = DO

2- Modelling N_2 for the GO

Here the independent variables for both coagulants will be:

X_1 = pH, X_2 =N_1 , X_3 = TMP and X_4 = GO

3- Modelling N_2 for the TO

Here the independent variables for both coagulants will be:

X_1 = pH, X_2 =N_1 , X_3 = TMP and X_4 = TO

3. Results and discussion

Table 2 shows the variation of DO and turbidity removal efficiency $R(\%)$ for both coagulants for a constant Flocculator-Velocity-Gradient (G1), constant Flocculation-Period (T1) and variable Coagulant-Dose (D1). Table 3 shows the variation of GO and residual turbidity for both coagulants at DO and T1 = 20 min., while Table 4 shows the variation of TO and residual turbidity for both coagulants at DO and G1 = 25l/s.

Table 2: Variation of DO and R (%) for G1 = 25 1/s, T1 = 20 min and variable D1.

Date	River Water Properties			Cactus Coagulation			Okra Coagulation		
	pH	N_1 (NTU)	TMP (°C)	DO (mg/l)	N_2 (NTU)	R (%)	DO (mg/l)	N_2 (NTU)	R (%)
29/8/2014	8.20	900	34	2.0	296	67.1	10.0	348	61.3
25/9/2014	8.19	659	29	8.0	59	91.0	12.0	69	89.5
16/10/2014	7.73	339	25	0.5	27.57	91.9	0.5	32.3	90.5
26/11/2014	8.14	319	17	1	33.45	89.5	8.0	35.29	88.9
24/12/2014	8.09	12.18	14	1	0.00	100	1.0	0.00	100
23/1/2015	8.07	18.36	13	8.0	9.16	50.1	10.0	8.43	54.1
26/2/2015	8.18	30.72	15	6.0	15.33	50.1	14.0	12.21	60.3
27/3/2015	8.19	38.27	19	12.0	13.64	64.4	20.0	12.57	67.2
30/4/2015	8.09	26.41	26	4.0	3.33	87.4	2.0	3.52	86.7
28/5/2015	7.82	18.27	30	12.0	11.13	39.1	12.0	11.75	35.7
11/6/2015	7.80	24.68	30	1.0	7.09	71.3	8.0	7.8	68.4
23/7/2015	7.81	13.40	35	16.0	4.97	62.9	16.0	2.23	83.4
Average						72.1			73.8

Table 3: Variation of GO and N_2 at DO (which resulted from Table 1) and T1= 20 min.

Date	River Water Properties			Cactus Coagulation		Okra Coagulation	
	pH	N_1 (NTU)	TMP (°C)	GO (l/s)	N_2 (NTU)	GO (l/s)	N_2 (NTU)
29/8/2014	8.20	900	34	45	158	45	170
25/9/2014	8.19	659	29	25	59	25	69
16/10/2014	7.73	339	25	25	27.57	25	32.3
26/11/2014	8.14	319	17	25	36.73	25	24.8
24/12/2014	8.09	12.18	14	25	0	55	0
23/1/2015	8.07	18.36	13	25	9.16	25	8.43
26/2/2015	8.18	30.72	15	25	15.33	25	12.21
27/3/2015	8.19	38.27	19	25	13.64	25	12.57
30/4/2015	8.09	26.41	26	25	2.29	25	1.84
28/5/2015	7.82	18.27	30	35	7.2	35	6.72
11/6/2015	7.80	24.68	30	55	4.98	35	3.32
23/7/2015	7.81	13.40	35	35	3.02	35	2.23

Table 4: Variation of TO and N_2 at DO (which resulted from Table 1) and G1= 25 1/s.

Date	River Water Properties			Cactus Coagulation		Okra Coagulation	
	pH	N_1 (NTU)	TMP (°C)	TO (min.)	N_2 (NTU)	TO (min.)	N_2 (NTU)
29/8/2014	8.203	900	34	23	253	23	257
25/9/2014	8.198	659	29	20	59	23	69
16/10/2014	7.734	339	25	20	25	20	32.3
26/11/2014	8.145	319	17	30	28.18	30	29.18
24/12/2014	8.090	12.18	14	20	0	20	0
23/1/2015	8.075	18.36	13	20	9.16	20	8.43
26/2/2015	8.183	30.72	15	26	13.68	20	12.21
27/3/2015	8.192	38.27	19	20	13.64	20	12.57
30/4/2015	8.091	26.41	26	20	3.33	26	3.33
28/5/2015	7.82	18.27	30	30	8.94	30	10.61
11/6/2015	7.80	24.68	30	30	4.26	30	4.11
23/7/2015	7.816	13.40	35	26	3.87	20	2.23

3.1. Modelling residual turbidity (N_2) for Optimum-Coagulant-Dose (DO)

Applying the data which resulted from Table 2 in the multiple regression model represented by equation 5, and analysing using SPSS version 20, the appropriate stepwise multiple regression model for cactus was:

N_2 (Cactus) = -6.765 + 0.234 (N_1) + e (6)

This means that the independent variables of pH, TMP and DO were insignificant statistically. The above regression gave F-ratio = 26.543 compared to the theoretical F (0.01, 1, 10) = 10.04 (which resulted from the tables); this means that regression (6) was highly significant. The obtained R^2 value, 0.726, indicates that the regression contribution ratio was very acceptable [35]. Additionally, the One-Sample Kolmogorov-Smirnov test gave the calculated statistic $|D_{max}|$= 0.286 which was insignificant compared to $D_{12}^{0.05}$ = 0.375 (from tables at α=0.05), indicating that e was normally distributed. The Durbin-Watson ratio was d = 1.784, indicating that e was serially uncorrelated (independently distributed). This proved that error term was NID (0, 1). The appropriate regression model for okra was:

N_2 (Okra) = -10.271 + 0.278(N_1) + e (7)

This means that the independent variables of pH, TMP and DO were insignificant statistically.

The above regression gave F-ratio = 27.048 compared to the theoretical F (0.01, 1, 10) = 10.04 (which resulted from the tables); this means that regression (7) was highly significant. The regression contribution ratio was $R^2 = 0.73$. Also, the One-Sample Kolmogorov-Smirnov test gave the calculated statistic | D_{max} |= 0.301 which was insignificant compared to $D_{12}^{0.05}$ = 0.375 (from tables at α=0.05), indicating that e was normally distributed. The Durbin-Watson ratio was d = 1.796, indicating that the e was serially uncorrelated (independently distributed). This proved that residuals were NID (0,1).

3.2. Modelling residual turbidity (N_2) for Optimum-Flocculator-Velocity-Gradient GO

Applying the data which resulted from Table 3 in the multiple regression model represented by equation 5, and analysing using SPSS version 20, the appropriate stepwise multiple regression model for cactus was:

N_2 (Cactus) = -0.155 + 0.137(N_1) + e (8)

The above regression gave F-ratio = 59.805 compared to the theoretical F (0.01, 1, 10) = 10.04 (which resulted from the tables); this means that regression (8) was highly significant. The regression contribution ratio was $R^2 = 0.857$. In addition, the One-Sample Kolmogorov-Smirnov test gave the calculated statistic | D_{max} |= 0.214 which was insignificant compared to $D_{12}^{0.05}$ = 0.375 (from tables at α=0.05), indicating that e was normally distributed. The Durbin-Watson ratio was d = 1.609, indicating that e was serially uncorrelated (independently distributed). This proved that residuals were NID (0, 1). The appropriate regression model for okra was:

N_2 (Okra) = -1.792 + 0.152(N_1) + e (9)

The above regression gave F-ratio = 72.989 compared to the theoretical F (0.01, 1, 10) = 10.04 (which resulted from the tables); this means that regression (8) was highly significant. The regression contribution ratio was $R^2 = 0.880$. In addition, the One-Sample Kolmogorov-Smirnov test gave the calculated statistic | D_{max} |= 0.241 which was insignificant compared to $D_{12}^{0.05}$ = 0.375 (from tables at α=0.05), indicating that e was normally distributed. The Durbin-Watson ratio was d = 1.593, indicating that e was serially uncorrelated (independently distributed). This proved that residuals were NID (0,1).

3.3. Modelling residual turbidity (N_2) for Optimum-Flocculation-Period (TO*)*

Applying the data which resulted from Table 4 in the multiple regression model represented by equation 5, and analysing using SPSS version 20, the appropriate stepwise multiple regression model for cactus was:

N_2 (Cactus) = -5.625 + 0.204(N_1) + e (10)

The above regression gave F-ratio = 30.189 compared to the theoretical F (0.01, 1, 10) = 10.04 (which resulted from the tables); this means that regression (10) was highly significant. The regression contribution ratio was $R^2 = 0.751$. In addition, the One-Sample Kolmogorov-Smirnov test gave the calculated statistic | D_{max} |= 0.286 which was insignificant compared to $D_{12}^{0.05}$ = 0.375 (from tables at α=0.05), indicating that e was normally distributed. The Durbin-Watson ratio was d = 1.722, indicating that the residuals were serially uncorrelated (independently distributed). This proved that residuals were NID (0, 1). The appropriate regression model for okra was:

N_2 (Okra) = -5.896 + 0.213(N_1) + e (11)

The above regression gave F-ratio = 36.839 compared to the theoretical F (0.01, 1, 10) = 10.04 (which resulted from tables); this means that regression (11) was highly significant. The regression contribution ratio was $R^2 = 0.880$. In addition, the One-Sample Kolmogorov-Smirnov test gave the calculated statistic | D_{max} |= 0.289 which was insignificant compared to $D_{12}^{0.05}$ = 0.375 (from tables at α=0.05), indicating that e was normally distributed. The Durbin-Watson ratio was d = 1.742, indicating that the residuals were serially uncorrelated (independently distributed). This proved that residuals were NID (0, 1).

A close analysis of the results of statistical models given by equations (6), (7), (8), (9), (10) and (11), together with the results of tables 1, 2 and 3 revealed the following:

1- That in terms of the Optimum-Coagulant-Dose, Optimum-Flocculator-Velocity-Gradient and Optimum-Flocculation-Period, when modelling the residual turbidity it was found that initial turbidity was the only significant variable for both cactus and okra.

2- That model (8) for cactus (in terms of Optimum-Flocculator-Velocity-Gradient) gave the highest coefficient of determination($R^2 = 0.857$).

3- That model (9) for okra (in terms of Optimum-Flocculator-Velocity-Gradient) gave the highest coefficient of determination($R^2 = 0.880$).

4- That DO ranged between 0.5 and 12 mg/l for cactus and between 0.5 and 14 mg/l for okra, according to Table 2.

5- That GO ranged between 25 and 55 1/s for cactus and okra, according to Table 3.

6- That TO ranged between 20 and 30 min. for cactus and okra, according to Table 4.

7- That models (8) and (9) were the most reliable models that can predict residual turbidity of the Euphrates river/Al-Mashroo canal/Al-Mussaib/Iraq, given the initial turbidity.

4. Conclusion

From the results of the study, it was concluded that cactus (*Opuntia spp*.) and okra were of similar coagulation-flocculation properties, and they were both competent for turbidity removal, which in turn indicates the possibility of using these coagulants in large-scale field applications. Additionally, according to the environmental parameters recorded during the period of study and the statistical analysis, two facts were concluded. The first fact was that controlling the Optimum Velocity Gradient of the Coagulation-Flocculation process gave the highest contribution ratio of the models, as reported by equations (8) and (9). The second fact was that the most significant parameter (statistically) in the flocculation process was the initial turbidity, as shown by equations (6), (7), (8), (9), (10) and (11).

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References

[1] A. Koohestanian, M. Hosseini, and Z. Abbasian, The Separation Method for Removing of Colloidal Particles from Raw Water. American-Eurasian J. Agric. & Environ. Sci., 4, (2008) 266-273.

[2] M. Dixon, C. Staaks, R. Fabris, V. Vimonses, C. W. Chow, S. Panglisch, J. A. van Leeuwen, and M. Drikas, The impact of optimised coagulation on membrane fouling for coagulation/ultrafiltration process. Desalination and water treatment, 51, (2013) 2718-2725.

[3] C. D. Abel, R. C. Vortisch, J. P. Ntelya, S. K. Sharma, and M. D. Kennedy, Effect of primary effluent coagulation on performance of laboratory-scale managed aquifer recharge system. Desalination and Water Treatment, 55, (2015) 1413-1421.

[4] K. S. Hashim, A. Shaw, R. Al Khaddar, M. Ortoneda Pedrola, and D. Phipps, Defluoridation of drinking water using a new flow column-electrocoagulation reactor (FCER) - Experimental, statistical, and economic approach. J Environ Manage, 197, (2017) 80-88.

[5] K. S. Hashim, R. A. Khaddar, N. Jasim, A. Shaw, D. Phipps, P. Kota, M. O. Pedrola, A. W. Alattabi, M. Abdulredha, and R. Alawsh, Electrocoagulation as a green technology for phosphate removal from River water. Separation and Purification Technology, 210, (2018) 135-144.
[6] M. M. Emamjomeh, Electrocoagulation technology as a process for defluoridation in water treatment, PhD thesis, School of Civil, Mining and Environmental Engineering, University of Wollongong, Australia., 2006.
[7] K. S. Hashim, I. Adeola Idowu, N. Jasim, R. Al Khaddar, A. Shaw, D. Phipps, P. Kot, M. Ortoneda Pedrola, A. W. Alattabi, M. Abdulredha, R. Alwash, K. H. Teng, K. H. Joshi, and M. Hashim Aljefery, Removal of phosphate from River water using a new baffle plates electrochemical reactor. MethodsX, 5, (2018) 1413-1418.
[8] A. W. Alattabi, C. B. Harris, R. M. Alkhaddar, K. S. Hashim, M. Ortoneda-Pedrola, and D. Phipps, Improving sludge settleability by introducing an innovative, two-stage settling sequencing batch reactor. Journal of Water Process Engineering, 20, (2017) 207-216.
[9] A. W. Alattabi, C. Harris, R. Alkhaddar, A. Alzeyadi, and K. Hashim, Treatment of Residential Complexes' Wastewater using Environmentally Friendly Technology. Procedia Engineering, 196, (2017) 792-799.
[10] K. S. Hashim, A. Shaw, R. Al Khaddar, M. O. Pedrola, and D. Phipps, Energy efficient electrocoagulation using a new flow column reactor to remove nitrate from drinking water - Experimental, statistical, and economic approach. J Environ Manage, 196, (2017) 224-233.
[11] S. Wang, Evaluation of Potassium Ferrate (VI) as an Oxidant and Coagulant for Water Treatment, PhD thesis, University of Surrey, Surrey, United Kingdom, 2003.
[12] K. S. Hashim, A. Shaw, R. Al Khaddar, M. O. Pedrola, and D. Phipps, Iron removal, energy consumption and operating cost of electrocoagulation of drinking water using a new flow column reactor. Journal of Environmental Management, 189, (2017) 98-108.
[13] C.-Y. Yin, Emerging usage of plant-based coagulants for water and wastewater treatment. Process Biochemistry, 45, (2010) 1437-1444.
[14] M. Abdulredha, A. Rafid, D. Jordan, and K. Hashim, The development of a waste management system in Kerbala during major pilgrimage events: determination of solid waste composition. Procedia Engineering, 196, (2017) 779-784.
[15] M. Abdulredha, R. Al Khaddar, D. Jordan, P. Kot, A. Abdulridha, and K. Hashim, Estimating solid waste generation by hospitality industry during major festivals: A quantification model based on multiple regression. Waste Manag, 77, (2018) 388-400.
[16] L. G. Torres, and S. L. Carpinteyro-Urban, Use of Prosopis laevigata seed gum and Opuntia ficus-indica mucilage for the treatment of municipal wastewaters by coagulation-flocculation. Natural Resources, 3, (2012) 35.
[17] L. Gomes, E. P. Troiani, G. R. Malpass, and J. Nozaki, Opuntia ficus indica as a polyelectrolyte source for the treatment of tannery wastewater. Desalination and Water Treatment, 57, (2016) 10181-10187.
[18] Y. A. E. I. Nougbodé, C. P. Agbangnan, A. Y. Koudoro, C. A. Dèdjiho, M. P. Aïna, D. Mama, and D. C. K. Sohounhloué, Evaluation of the Opuntia dillenii as natural coagulant in water clarification: case of treatment of highly turbid surface water. Journal of water resource and Protection, 5, (2013) 1242.
[19] B. Mounir, Z. Abdeljalil, and A. Abdellah, Comparison of the efficacy of two bioflocculants in water treatment. Int J Sci Eng Technol, 3, (2014) 734-737.

[20] N. Taa, M. Benyahya, and M. Chaouch, Using a bio-flocculent in the process of coagulation flocculation for optimizing the chromium removal from the polluted water. Journal of Materials and Environmental Science, 7, (2016) 1581-1588.
[21] S. Vishali, and R. Karthikeyan, Cactus opuntia (ficus-indica): an eco-friendly alternative coagulant in the treatment of paint effluent. Desalination and Water Treatment, 56, (2015) 1489-1497.
[22] K. A. Young, The Mucilage of Opuntia Ficus Indica: a natural, sustainable, and viable water treatment technology for use in rural Mexico for reducing turbidity and arsenic contamination in drinking water, MSc thesis, College of Engineering, University of South Florida, USA., 2006.
[23] A. A. Al-Samawi, and A. R. Hama, The use of Okra as a coagulant and coagulant aids in the removal of heavy metals of solid waste leachates. Engineering and Technology Journal, 30, (2012) 3524-3535.
[24] R. Binayake, and M. Jadhav, Applications of natural coagulants in water purification. International journal of advanced technology and civil engineering, 2, (2013) 118-123.
[25] E. De Jesus, P. V. Cruz, J. A. Pacífico, and A. S. Silva, Removal of turbidity, suspended solids and ions of Fe from aqueous solution using okra powder by coagulation-flocculation process. Am J Water Resour, 1, (2013) 20-24.
[26] S. S. Thakur, and S. Choubey, Assessment of coagulation efficiency of Moringa oleifera and Okra for treatment of turbid water. Archives of Applied Science Research, 6, (2014) 24-30.
[27] Y. O. RAJI, L. ABUBAKAR, S. O. GIWA, and A. GIWA, Assessment of Coagulation Efficiency of Okra Seed Extract for Surface Water Treatment. International Journal of Scientific & Engineering Research, 6, (2015) 719-725.
[28] E. Shokralla, An investigation into natural coagulants, M.Sc. Thesis, Building and Construction Department, University of Technology, Iraq, 1995.
[29] B. Shilpaa, K. Akankshaa, and P. Girish, Evaluation of cactus and hyacinth bean peels as natural coagulants. International Journal of Chemical and Environmental Engineering, 3, (2012).
[30] N. Al-Saati, E. Hwaidi, and S. Jassam, Comparing cactus (Opuntia spp.) and alum as coagulants for water treatment at Al-Mashroo Canal: a case study. International journal of environmental science and technology, 13, (2016) 2875-2882.
[31] M. Eddy, Wastewater Engineering-Treatment, Disposal, Reuse, McGraw-Hill Inc., New York, 1979.
[32] T. J. McGhee, and E. W. Steel, Water supply and sewerage, McGraw-Hill Inc., New York, 1991.
[33] S. Kawamura, Integrated design and operation of water treatment facilities, John Wiley & Sons Inc., New York, 2000.
[34] R. M. Bethea, B. S. Duran, and T. L. Boullion, Statistical methods for engineers and scientists, Marcel Dekker Inc., New York, 1995.
[35] J. Pallant, SPSS survival manual, McGraw-Hill Inc., Sydney, 2005.